Journal of the History of Biology (2006) 39:707–735
DOI 10.1007/s10739-006-9110-8

Mice and the Reactor: The "Genetics Experiment" in 1950s Britain

SORAYA DE CHADAREVIAN
Department of History and Philosophy of Science
University of Cambridge
Free School Lane
Cambridge, CB2 3RH
UK
E-mail: sd10016@cam.ac.uk

Abstract. The postwar investments by several governments into the development of atomic energy for military and peaceful uses fuelled the fears not only of the exposure to acute doses of radiation as could be expected from nuclear accidents or atomic warfare but also of the long-term effects of low-dose exposure to radiation. Following similar studies pursued under the aegis of the Manhattan Project in the United States, the "genetics experiment" discussed by scientists and government officials in Britain soon after the war, consisted in large-scale low-dose irradiation experiments of laboratory animals to assess the effects of such exposures on humans. The essay deals with the history of that project and its impact on postwar genetics. It argues that radiobiological concerns driven by atomic politics lay at the heart of much genetics research after the war and that the atomic links are crucial to understand how genetics became an overriding concern in the late 20th century.

Keywords: atomic age, atomic fallout, low-dose radiation debate, mice experiments, postwar genetics, radiation biology

Despite the pompous celebrations in 2003 of the fiftieth anniversary of the DNA double helix, it is now widely accepted that James Watson and Francis Crick's model of the structure of DNA did not make an immediate impact.[1] Yet even if the double helix did hardly create headlines in the 1950s, genetics stood very much on the agenda of governments at that time. Today this may seem a contradiction, but it was not before the late 1970s and 1980s that genetics became more generally equated with the study of DNA. To understand this transformation and the place that genetics occupies today, it is important to study in more depth the concerns and practices that propelled the interest in genetics in the preceding decades.

[1] Olby, 2003, p. 402. See also de Chadarevian, 2002, pp. 241–245.

A central set of concerns that drove genetic research after World War II was connected to the entangled military and civilian uses of atomic energy. In a timely declaration of the relevance of genetics to the atomic age, one of the first Nobel Prizes after the war went to Hermann J. Muller for his pre-war work on radiation-induced mutations. In his acceptance speech Muller underlined the deleterious effect of most mutations and ended with a strong plea to protect the human germ plasm, "the all-important material of which we are the temporary custodians", from damaging radiations.[2] In the study of the atomic bomb survivors of Hiroshima and Nagasaki that U.S. scientists started almost immediately after the war, the genetic studies dealing with the effects of the radioactive exposure on the pregnancies and children of the survivors attracted most attention. As has been shown, the investigations had far reaching diplomatic, political, military, scientific, and disciplinary implications.[3] The postwar development of atomic energy and especially the worldwide contamination with radioactive fallout from atmospheric nuclear bomb testing in the 1950s and early 1960s prompted intense fears of genetic hazards and calls for more genetic research.

In face of the dramatic dimensions of atomic warfare that threatened to make the world uninhabitable, it seems legitimate to ask why genetic questions, rather than more immediate questions concerning the health of the survivors, gained such importance. One explanation given is that the "long-term effects [of atomic exposure] were much less well known and therefore far more interesting", especially for the researchers involved in the survivor studies.[4] Yet rather than the novelty, the continuity with pre-war preoccupations regarding the "gene pool" of the population could provide an answer. As Diane Paul has argued, even if the terms introduced into the debate were new, as in the case of Muller's

[2] Muller, 1946.

[3] Beatty, 1991; Beatty, 1993; and Lindee, 1994.

[4] Hacker, 1987, p. 116. For a contemporary statement on the issue see Genetics Conference. Committee on Atomic Casualties. National Research Council, 1947. Radiation more generally generated acute public fear in the 20th century. This is often attributed to the fact that radiation is imperceptible to human senses and that its effects have no definite end. Genetics effects of radiation could be seen to epitomise these fears. Yet as Samuel Walker has argued, no attitude towards radiation can be explained independently of its historical context and especially of the ongoing debate on sufficient radiation protection; see Walker, 2000, especially pp. 145–153. On attitudes to radiation see also Weart, 1988.

use in 1951 of the supposedly more neutral term "load of mutation", the continuity with earlier eugenic concerns was often hard to disguise.[5]

The postwar investments by several governments into the development of atomic energy for military and peaceful uses fuelled the fears not only of the exposure to acute doses of radiation as could be expected from nuclear accidents or atomic warfare but also of the long-term effects of low-dose exposure to radiation. Following similar studies pursued under the aegis of the Manhattan Project in the United States, the "genetics experiment" discussed by scientists and government officials in Britain soon after the war, consisted in large-scale low-dose irradiation experiments of laboratory animals to assess the effects of such exposures on humans. This paper deals with the history of that project and its impact on postwar genetics.[6]

Other historians of science have pointed to the connections between genetics and nuclear politics.[7] However, there has been hardly any attempt to investigate these links in the history of genetics in Britain that, because of its embracement of a nuclear programme and its comparatively high investment into scientific research after the war, represents an important point of reference for developments both in the United States and Europe. More specifically, virtually no historical work has been done on the radiobiological work pursued at the site of the Atomic Energy Research Establishment at Harwell that stands at the centre of this study.[8] Finally, despite the fact that several historians have stressed

[5] Paul, 1987. Muller, who exposed vociferously the dangers of radiation from atomic energy for future generations, remained a strong promoter of eugenic ideas throughout his career. On Muller see Carlson, 1981. On the eugenic legacies of postwar genetics see also Kevles, 1995.

[6] Radiobiological investigations were also conducted on human subjects, including patients and volunteers. Following a television documentary entitled "Deadly experiments" and broadcast on Channel 4 in 1995 in which the MRC (among other funding bodies) stood accused of unethical research practices in a series of radiobiological experiments on human subjects performed between 1950 and 1970, the MRC set up an inquiry chaired by Rabbi Julia Neuberger. The final report of the committee refuted the implication that any of the research was conducted for military purpose, but admitted that the ethical research standards, even if following the practice of the time, fell below currently accepted standards (Neuberger, 1998).

[7] In addition to the references in n. 3, above, see Beatty, 1994; Kay, 2000; and Rader, 2004, Chapter 6. On the impact of the bomb on postwar biology more generally see Rasmussen, 1997.

[8] In her monumental history of the British atomic bomb project Margaret Gowing dedicated ample space to issues of health and safety in the nuclear establishments, but there is only one fleeting reference to the biological work done in tandem with work on atomic energy at Harwell; see Gowing, 1974b, p. 95. The low-dose irradiation experiments were only one of a large number of radiobiological projects pursued at the site.

the links between genetics and nuclear politics, the notion of this connection has not entered the mainstream accounts of postwar genetics, certainly not those presented to us in the course of the 50th anniversary of the DNA double helix that instead, and predictably so, very much centred on the double helix as the defining event in the history of postwar genetics. This paper contends that radiobiological concerns driven by nuclear politics lay at the heart of much genetics research after the war and that the atomic links are crucial to understand how genetics became an overriding concern in the late 20th century.

A Site for Radiobiological Research

After World War II Britain invested in atomic energy research and a national atomic bomb project. Simultaneously, the government called for research into the medical and biological applications of nuclear physics. While research on atomic energy was overseen, first, by the Ministry of Supply and, from 1954, by the newly created United Kingdom Atomic Energy Authority, research into the biological and medical effects of radiation became the responsibility of the Medical Research Council (MRC) that had seen its status greatly enhanced following its role in the wartime mobilisation.[9]

To carry out the newly set tasks, in 1946 the MRC created a committee, the MRC Committee on Medical and Biological Applications of Nuclear Physics, with a series of subcommittees, charged to deal with different aspects of the matter. There was a Subcommittee for the Protection against Hazards to Health, a Subcommittee for the Use of Tracer Elements in Research, and a Subcommittee for the Clinical Use of New Radioactive Materials and Appliances.[10]

Among the very first research projects discussed by the Protection Subcommittee was the plan of large-scale animal experiments to study

[9] The dual funding system represented a difference to the situation in the U.S. where the Atomic Energy Commission (AEC) both promoted atomic energy and was responsible to assess the health risks. The AEC came repeatedly under attack for its dual role; see for instance Hacker, 1994, pp. 199 and 254. The British Ministry of Supply represented something like the procurement executive of the Ministry of Defense. It existed in the period 1939–1959; see Edgerton, 1992.

[10] The existence of an additional committee, the Panel on Atomic Bomb Explosions, from 1949 also known as Sir Harold Himsworth's Private Panel, underlines the centrality of radiobiological issues to the MRC. In 1957 the panel was reconstituted as two committees to deal with civil and military nuclear hazards, respectively; see files F. 378–380, Joseph S. Mitchell Papers, Cambridge University Library.

the genetic effects of radiation. It was known that scientists at the University of Rochester had carried out extensive irradiation experiments on mice as part of the Manhattan Project. The results of these experiments were expected soon.[11] The initial plan was therefore that geneticists in Britain should not simply double the U.S. effort but instead embark on a long-term investigation of the genetic effects of radiation on rabbits to obtain data on another species. The prime mover behind this project was John Burdon Sanderson Haldane, then Professor of Genetics and Biometry at University College London, who had made his name in the field of genetics with his mathematical studies of natural selection in the 1930s. Although less well established than mice for genetic experiments, rabbits were extensively used in the laboratory and, for instance, were the standard organism for work on sex physiology. They were cheap to maintain and bred quickly.[12]

The subcommittee made a site visit to the British Chemical and Biological Defense Establishment at Porton to study the possibility of starting experiments there. Yet for a number of reasons, including the lack of accommodation and personnel and the quality of the animal strains, it decided against it. Instead the subcommittee investigated the possibility to start metabolic studies of radioisotopes, especially strontium, and of the spermatogenesis in monkeys.[13] The subcommittee, none the less, remained convinced of the urgency to start low-dose irradiation experiments. It consulted other geneticists besides Haldane, among them the Cambridge plant geneticist David Catcheside, and studied the suitability of other government sites, including the Agricultural Research Station at Compton and the Telecommunication

[11] Specifically on the mice irradiation experiments see Rader, 2004, pp. 226–227; on biomedical research under the aegis of the Manhattan Project more generally see Hacker, 1987. The eventual failure to publish the results of the Rochester experiments formed part of a more entrenched problem regarding the exchange of data between U.S. and British radiobiologists, agreements on the free flow of information in respect to biological and medical research of atomic energy notwithstanding.

[12] See J.B.S. Haldane to Sir Ernest Rock-Carling (Home Office), 29 April 1946; F. 287, Joseph S. Mitchell Papers, Cambridge University Library. Besides long-term experiments with rabbits and some experiments with monkeys, Haldane, following discussions with the radiologist Joseph S. Mitchell and the geneticist Lionel Penrose, also suggested to study the fertility and the "normality or otherwise" of the children of the workers at the Harwell site as well as those of radiologists and radiographers in England (ibid.). On rabbit breeding and the role of rabbits in genetical research in interwar and wartime Germany see Schwerin, 2004.

[13] "Metabolism of nuclear fission products and the effects of radioactive dusts," 16 July 1946; FD1/468, National Archives, Kew. The accumulation of radioactive strontium from fallout in the body became a major concern from the mid-1950s.

Research Establishment at Malvern, the main site for radar research since the latter part of the war. It also applied to the MRC Council for financial support.

Around that time, John Cockcroft, the director of the newly created Atomic Energy Research Establishment at Harwell in Oxfordshire, approached the MRC with the suggestion to appoint a Medical Director of Research to head the medical laboratory at the atomic energy establishment. The duties of the medical scientist were originally described as "to investigate the toxic actions of radioactive substances and to develop methods of protecting workers against them",[14] much like the medical research programme at the Manhattan Project of which Cockcroft, who had worked at the Chalk River atomic plant in Canada, was well aware. A Principal Medical Officer who was more directly responsible for the medical care and supervision of the health of all employees, was appointed by the Ministry of Health. In his clinical work he was to follow the advice of the research section.

The MRC, which was already committed to research into the hazards of and protection against radiation, was glad to accept the invitation to staff the research section. In 1947 a quickly growing Radiobiological Research Unit was inaugurated at the Harwell site under the directorship of John Loutit, a haemotologist who had headed one of the London Blood Depots during the war. Yet before agreeing to the deal, Edward Mellanby, the Secretary of the MRC, asked Cockcroft if "there was room to put up a good sized building for testing the effect of radiations on rabbits, of which a large number would be needed, probably a thousand at a time". Cockroft responded that "such work could be done quite easily".[15] From the beginning then, 30 acres of grassland in the southwest corner of the disused aerodrome outside the restricted area of Harwell were earmarked for MRC genetic experiments.

Safe Threshold or Linear Relationship?

Despite the high political priority attached to the low-dose irradiation experiments, nothing much did happen at Harwell for a while. Apparently this was in large part due to the uncompromising attitude of

[14] E. Mellanby to A. Barlow, 27 September 1946; FD1/468, National Archives.

[15] Note of 15 Nov 1946 by E. Mellanby; FD1/468, National Archives. Mellanby also mentioned that he wished to have Haldane's advice when needed on the project, but that he wanted to keep him out of the directing side.

Haldane who wanted the run of the place and no secrecy restriction attached to any of his workers. He also bemoaned that while Harwell could provide space and equipment, it lacked a "strong atmosphere of genetics."[16] Yet the inertia also marks the difference to the wartime mobilisation programmes.

Meanwhile, on Cockcroft's suggestion, work on the genetic effects on mice under chronic gamma irradiation started at the Institute of Animal Genetics in Edinburgh under the supervision of the distinguished embryologist and geneticist Conrad Waddington, the institution's new head.[17] The project was funded by the MRC. Loutit, the director of the Harwell Radiobiological Research Unit, was involved as a consultant.

The experiments picked up a tradition started by the geneticist Hermann J. Muller who had spent some time at Edinburgh in the late 1930s after leaving the Soviet Union to where he had emigrated from the United States. While at Edinburgh, Muller had pursued his investigations into the mutagenic effects of X-rays that he himself had first described 10 years earlier. With the beginning of the war, Muller had left Edinburgh, but his X-ray machine was still there. In addition to X-rays the group working on the project also used radium as irradiation source. The scientists involved in the research were two recruits from Ronald A. Fisher's Department of Genetics at Cambridge, Tobias Carter and Mary Lyons, and Rita Phillips, a young geneticist from Liverpool.

By 1947, when the Edinburgh experiments went under way, the house mouse was widely used as model organism for mammalian genetics, although its 20 chromosomes meant that mapping its genes presented considerable difficulties and no comprehensive linkage map yet existed. The Edinburgh scientists started their stock from a few pairs of inbred strains.[18] After experimenting with various methods to establish mutation rates, they eventually settled on what became known as the multiple-recessive method or single locus test. The first step involved constructing a stock of mice that was homozygous for (i.e., carried two doses of) several recessive mutations that could be easily identified and hence allowed for quick scanning. Seven mutations were

[16] Medical Research Council, Tolerance Doses Panel of the Protection Sub-Committee. Meeting of geneticists [minutes of meeting held on 28 October 1948]; F. 312, Joseph S. Mitchell Papers, Cambridge University Library.

[17] On genetics research in Edinburgh see Falconer, 1993.

[18] The CBA mice used at Edinburgh was an established strain first developed by L.C. Strong at Cold Spring Harbor in the 1920s. In their research papers the Edinburgh scientists did not specify where they acquired their first mice from, although Fisher is occasionally thanked for supplying mice mutants.

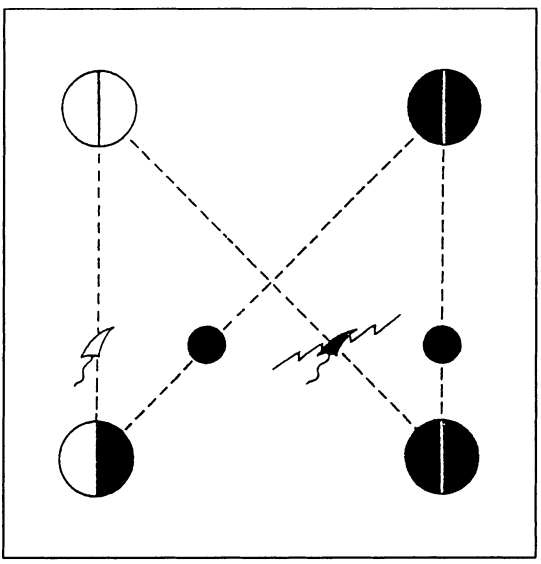

Figure 1. The multiple recessive method used to detect mutations. Irradiated wild-type male mice (top left) are crossed with non-irradated female mice carrying two doses of a recessive mutant gene (top right). All off-springs are wild-type (bottom left) except when a mutation to one of the recessive alleles has occurred in the sperm (bottom right). Source: M.T.C. Carter, F. Lyons and R.J.S. Phillips, "Induction of mutation in mice by chronic gamma irradiation: interim report." *British Journal of Radiology* 29 (1956), p. 107, Fig. 2. Courtesy of British Institute of Radiology.

chosen, including such characteristics as brown coat, short ears and pink eyes. In the experiments sperm from irradiated wild-type male mice was used to fertilise females carrying two doses of a recessive mutant gene. If irradiation had produced mutation in the male, the offspring would show the mutation. If no mutation occurred, the offspring would appear wild-type (Figure 1).

That germ cells were sensitive to radiation was already well established. The Edinburgh experiments were designed to determine whether there was a safe threshold or if the linear relationship between radiation dose and mutation rate held true for very low doses (see Figure 2). The question was of central importance for protection issues and for the atomic politics several governments, including Britain, were embracing.[19] Scientists were divided on the issue. Those who were concerned

[19] On the development of safety regulation for exposure to radiation and especially on the shift from the biological idea of a safe threshold to the political notion of a "permissible dose" see Hacker, 1987; 1994; and Walker, 2000. For a specific focus on the British context and the question of genetic hazard see Pound, 1994.

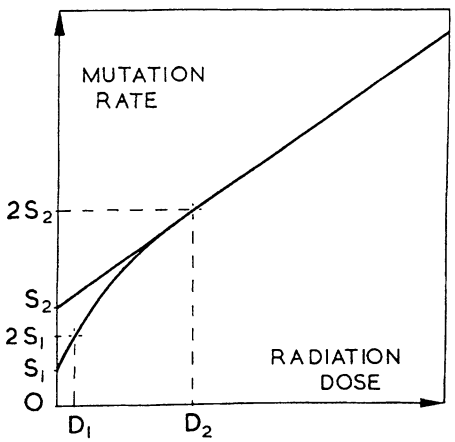

Figure 2. Safe threshold or linear relationship between radiation dose and mutation rate for low doses? M.T.C. Carter, F. Lyons and R.J.S. Phillips, "Induction of mutation in mice by chronic gamma irradiation: interim report." Source: *British Journal of Radiology* 29 (1956), p. 107, Fig. 1. Courtesy of British Institute of Radiology.

with somatic damage tended to take the view, which they shared with pharmacologists, that if the accumulated radiation dose were sufficiently low, there would be no induced damage. In contrast, scientists who were concerned with genetic effects tended to agree with the thesis originally enunciated by Muller that the induced genetic damage was directly proportional to the accumulated dose.[20] The experiments in course at Edinburgh were designed to supplement data collected in studies undertaken at Oak Ridge, Tennessee, the uranium production site of the Manhattan Project, to which an expanding biological division had been added. As had transpired, the investigations in the U.S. were concerned

[20] Tobias C. Carter, "Early days of MRC radiation genetics in retrospect," talk presented at the 25th anniversary of the occupation of the buildings of the Radiobiology Unit at Harwell, 20 March 1979; MRC Library, Harwell. Following a similar line of argumentation, Christopher Jolly in his PhD dissertation has provided a detailed analysis of the disciplinary reasons that led geneticists and physicians in the U.S. to take opposite views in the debate; see Jolly, 2003. Jolly acknowledges that other factors might have played a role as well. To determine these factors a careful social and political mapping of the scientists involved in the debate would be needed. For a preliminary study in this direction regarding the US context see Kopp, 1979. Radiobiological research and applications were often seen, not least by the funding agencies themselves, as providing a "silver lining" for the military development of atomic energy (Rasmussen, 1997), but investigations on the effects of radiation also provided scientific arguments for opponents of nuclear politics.

with the effect of higher doses of radiation applied over a shorter time span.[21]

The scientists at Edinburgh successfully set up their testing system, but soon it became clear that to achieve statistically significant results in a "reasonable time span" (i.e., in 10 rather than 20 years time), the operation needed to be scaled up. The group calculated that it needed to raise 150,000 mice from irradiated fathers. This meant that together with the necessary control experiments and some other experiments the group was running, it would need 11 breeding rooms and a total of 2,200 cages instead of the available five breeding rooms.[22] Such expansion was impossible at Edinburgh or in any other University setting.

Waddington argued that the problems connected with the genetic effects of ionising radiation on mammals were going to be "a problem for our civilisation for as far ahead as one can possibly see" and that it would be entirely proper for the MRC to consider research on such a subject as suitable for a long-term commitment.[23] At this juncture Loutit successfully negotiated the move of the Edinburgh group to the MRC unit at Harwell. One of the arguments used to justify the move was that the future of the atomic energy programme for the industrial production of power to which Harwell scientists were committed could depend on genetic factors.

Apart from the possibility to expand its operation, the Edinburgh group was attracted to Harwell by the unique radiation sources that were available on site. The atomic energy establishment maintained two natural uranium piles that provided sources of radiation suited for different kinds of radiobiological experiments. The pile known by the acronym GLEEP (graphite low energy experimental pile) provided fast neutrons that could be applied to large numbers of mice to mimic daily irradiation such as might be received by occupationally exposed workers.[24] In contrast, BEPO (British experimental pile "0") provided neutrons at a higher dose rate that could be used to mimic exposure

[21] On the radiobiological division at Oak Ridge see Rader, this issue.

[22] T. Carter to C. Waddington, Memoranda, 9 and 16 June 1953; FDI/8703, National Archives.

[23] C. H. Waddington to H. Himsworth, 22 June 1953; FD1/8703, National Archives.

[24] GLEEP was the first nuclear reactor built in Europe. Established in 1947, it was in operation until the early 1990s as a materials testing device and was dismantled only very recently; see Brown, 2004a. BEPO was the second UK reactor. The air-cooled uranium reactor was used to demonstrate that commercial power reactors could be viable. It became the forerunner to the piles at Windscale, Britain's first plutonium factory. It was dismantled in 1968.

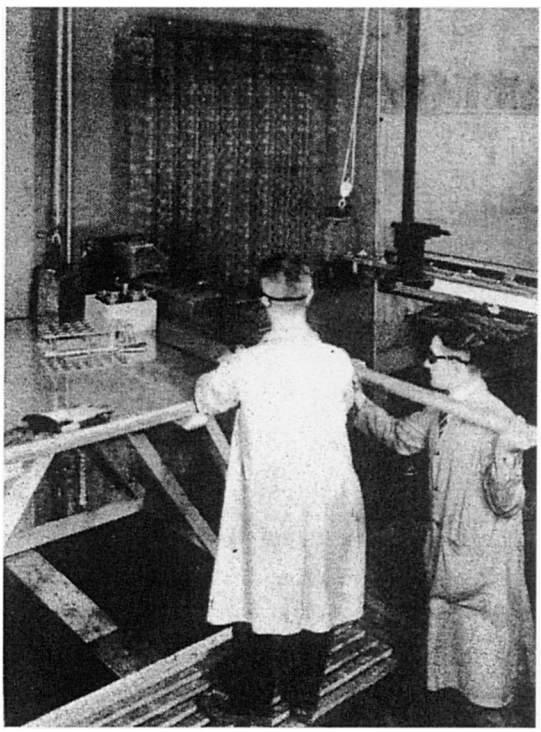

Figure 3. Samples are loaded into GLEEP for irradiation and the production of radioisotopes. Source: *A.E.R.E. The Atomic Energy Research Establishment*. Harwell, Berkshire, 1949 [booklet]. Courtesy of UKAEA.

received in nuclear accidents. Both piles were also used to produce radioisotopes that were gaining increasing importance in biomedical research (Figure 3).[25]

By the mid-1950s, Carter, Lyons and Phillips had moved to the MRC unit at Harwell, with Carter becoming the head of the new Genetic Section. The researchers had used the move to renew their mice stocks. New stocks were acquired in particular from Oak Ridge where William and Liane Russell were performing irradiation experiments using a very similar method known as the single locus test. Using the same mice and

[25] On the production, circulation and early uses of radioisotopes see the articles by Creager, Gaudillière and Santesmases in this volume. On the production and clinical use of radioisotopes in Britain see Kraft, 2006.

Figure 4. Mary Lyons with mice flats. Source: Oxford Mail 12 April 1955. Courtesy of Newsquest (Oxfordshire) Ltd.

adopting the U.S. method in detail was to ensure that future results would be more closely comparable[26] (Figure 4).

Public Concerns

The establishment of the Genetic Section at Harwell happened at a time when a series of test explosions of a new generation of nuclear bombs, the vastly more destructive H-bombs, raised new public fears of atomic fallout, and the genetic hazards of radiations – not just for people working in nuclear establishments, but for the population at large – became a burning political issue, in Britain and world-wide. The hydrogen bomb, exploded by the U.S. in 1954 on Bikini Island, yielded an explosion of about 1,000 times the power of the atomic bomb dropped on Hiroshima. The accidental irradiation of a Japanese fishing boat, the Lucky Dragon, 80 miles from the test site that led to signs of

[26] T. Carter to C. Waddington, Memorandum, 9 June 1953; FDI/8703, National Archives. See also Rader, 2004, p. 246. In fact, the collaboration between the two groups remained difficult for reasons that are hard to pin down. Researchers at Harwell put it down to the reluctance of the Russells to share information with the British researchers as well as to keep to agreements. Following discussions with the Russels in 1953, the British researchers decided to rely on American efforts to measure the spontaneous mutation rate. A few years later they bemoaned that despite repeated requests they had obtained no information on the experiments. Later it transpired that the Americans had not undertaken the work nor were they willing to undertake it, thus upsetting the planning of the British group; see T. Carter, "The future of genetical research at Harwell," 18 October, 1956; FDI/8706, National Archives. See also below.

radiation sickness in all its 23 occupants and the subsequent death of one of the crew members, raised an alarm signal. The events came to symbolise the growing concern regarding fallout.[27]

The British Parliament discussed the issue in the spring of 1955.[28] In addition to offering insights into the political discussion regarding genetics research, the debate that was opened by Dr Edith Summerskill, MP of the Labour opposition, offers a glimpse into the way gender relations entered the political arena in connection with the threat of nuclear weapons. In her opening remarks Summerskill, who had a medical degree and had been Minister of National Insurance and Industrial Injuries in the second Labour government after the war, pointed out that it was the first time in British parliamentary history that a woman member opened and another woman member would wind up a debate. She agreed to be corrected on this point–there had been an all-women debate on a previous occasion–but insisted on the unique importance of the subject matter to be discussed. She went on to underline that the issue raised, that of "modern war weapons", was one which "women generally are only too ready to cede to men". She excused herself for intruding into what until then had been a male sphere, but passionately argued that atomic weapons had broken down the traditional division between "war as male past time" and "procreation as female domain". The new weapons had properties that threatened "women's creative power" and would have an impact on generations to come.[29] Summerskill promised not to use too technical language, excusing herself when she did so, but was well equipped with figures and quotes from respected scientists who had warned against the dangers of the atmospheric test explosions. The authorities quoted included the professor of biophysics in the Medical School of Osaka University in Japan who had examined people exposed to the Bikini test explosion in March 1954, finding that their blood forming functions as well as their sperm counts were seriously affected and pointing to the danger of malformation in the next generation; the Federation of American Scientists; British Nobel Prize winning physiologist Edgar Adrian; and geneticists Curt Stern and Alfred H. Sturtevant of the California Institute of Technology. Summerskill stressed that she did not intend to make sensational statements about the

[27] For a contemporary exposition of the fallout problem see Pirie, 1958; and Fowler, 1960.

[28] Nuclear explosions (genetic effects), 1955.

[29] Ibid., pp. 1881–1886. In later years the women opposition to nuclear weapons in Britain found expression in the Greenham Common Women's Peace Camp that remained an active centre of resistance until very recently.

genetic effects of experiments with hydrogen bombs, but that there was a *prima facie* case for the examination of the whole problem. By the time of the debate, 65 nuclear explosions had taken place, with the U.S. signing responsible for 50 of them, the Soviet Union for 12 and Britain for 3. Only a handful of the test explosions were of H-bombs, but their number was expected to rise.

Summerskill's statement was followed by an extensive discussion at the end of which the House of Commons resolved that "pending a satisfactory result of the intensive efforts which are being made to achieve a comprehensive scheme of disarmament, [it] welcomes Her Majesty's government's decision *to continue and expand research in this country on the medical and biological aspects of nuclear energy* and to collaborate by every practical means with those countries with whom arrangements already exist and with such others as can usefully be brought into consultation".[30] This was a watered down resolution of the one originally proposed by Summerskill that depicted the threat to humanity from the continuing nuclear explosions in much starker terms. It none the less put the issue on the table.

Following the Parliamentary debate the British Government asked the MRC to report on the medical aspects of nuclear radiation. Among the members of the high-powered committee appointed by the MRC and chaired by its Secretary were Cockcroft, Loutit, Waddington, the epidemiologist Austin Bradford Hill, the Cambridge radiologist Joseph Mitchell and the geneticist Lionel Penrose. Carter and William M. Court-Brown, who had participated in the survivor studies in Japan and, together with the epidemeologist Richard Doll, was engaged in a major study on the leukaemia-inducing effect of X-ray therapy, were joint technical secretaries. The much awaited report *Hazards to Man of Nuclear and Allied Radiations* was presented to Parliament in 1956, as a White Paper.[31]

The report highlighted the cumulative effect of radiation and hence the need to limit the use of all sources of radiation. It concluded that the current levels of radioactivity from atmospheric fallout were negligible

[30] Ibid., p. 1947 (my italics).

[31] Medical Research Council, 1956. Besides participating in the discussions and drafting of the MRC report Carter, following talks with the Secretary of the MRC, also drew up a comprehensive plan for genetic research in Britain with the final aim of establishing the genetic effects of chronic irradiation on human populations; see T. Carter to Harold Himsworth, 25 April 1955, with attached document "Plan for research in Great Britain into the inherited effects on human populations of chronic exposure to ionising radiations;" FDI/8706, National Archives. The document formed part of the MRC's discussions regarding the expansion of its genetic programme (see below).

compared to both the natural level of radioactivity and in comparison to the use of radiation in the clinic that represented the most serious concern, but it warned that continued hydrogen bomb testing could radically change the picture. It pointed to the cumulative and irreparable genetic effect of radiation as well as to the hazards deriving from the accumulation in the body of radioactive elements such as strontium, and it reiterated the urgent need for further medical and genetic research. After discussion in Parliament,[32] the British government made the report available to the United Nations Scientific Committee on the Effects of Atomic Radiations, (also known as UNSCEAR), established in 1955.

The publication of the MRC report closely coincided with the publication of a corresponding report prepared by the U.S. National Academy of Sciences that reached a similar conclusion. Recent research has shown that this was no coincidence but rather the result of a coordinated effort intended to avoid conflict and maximise the effect of the two reports.[33] As a consequence of both the reports the International Commission for Radiation Protection tightened the permissible limits for radiation exposure, lowering its suggested maximum occupational dose from 15 to 5 rems per year for whole-body exposure.[34] As before, the recommended maximum dose for population exposure lay at 1/10 of the levels that applied to radiation workers. The lower level was justified by the fact that a much larger number of people was concerned and that the general population could be monitored less effectively than

[32] Nuclear and allied radiation (hazards to man), 1956. Apart from this more extended discussion the issue of genetic effects from nuclear radiation was the subject of numerous oral and written questions and answers in Parliament, both before and after the publication of the White Paper.

[33] *The Biological Effects of Atomic Radiation*, 1956 (also known as the BEAR Report) and Hamblin, 2006. Hamblin also sheds light on the U.S. National Academy of Sciences' public relation effort put in place to ensure a positive reception of the report. The close coordination between the U.S. and British effort in respect to the two reports stands in contrast to the tensions between radiobiologists at Harwell and Oak Ridge documented in the present essay. However, Hamblin points to similar tensions between the AEC and the geneticists serving on the BEAR committee in respect to the AEC's control over the release of genetic data; see Hamblin, 2006, p. 7. On the AEC's "negative information policy" see also Jolly, 2003, p. 14. Following the British and American report, the World Health Organisation convened an international study group dedicated specifically to gain understanding of the genetic effects of ionizing radiation. The report called on governments to recognise the need for more human and experimental genetic research and to make substantial financial provisions to that end; see *Effect of Radiation on Human Heredity*, 1957.

[34] The rem represents a measure for the biologically effective dose of radiation. It varies from one radiation source to another.

industrial workers. Although both reports were quite cautious in their assessment of the dangers from radiation, they were also credited with having played a part in shifting public opinion and achieving an international agreement to ban atmospheric testing of atomic weapons, as laid down in the Limited Test Ban Treaty of 1963.[35] Other dramatic events helped achieve that result.

The issues raised in the two reports gained fresh salience following the leak of radioactivity from Britain's new plutonium factory at Windscale in Cumbria in 1957. The accident, caused by the outbreak of a fire in one of the reactors following a routine operation, was the worst nuclear accident the world had seen so far. Plant workers as well as the local population were exposed to radiation doses that much exceeded the limits of the maximum life time doses. 200 square miles of countryside were declared to be contaminated and milk produced in this area was banned from being sold for several weeks. Later official reports estimated that 32 deaths and at least 260 cases of cancer could be attributed to the radiation release. Independent experts suggest that more than 1,000 lives were claimed.[36] In Britain the decision of the government to follow the U.S. and Soviet lead and develop an H-bomb had stirred public opposition against the politics of nuclear deterrence embraced after the war. The Windscale accident brought the issues to a head. It precipitated the formation of the Campaign for Nuclear Disarmament (CND) that, in its first years, assembled many thousand protesters. Young and old in impressive numbers joined the CND Easter marches – first to, in later years from the Atomic Weapons Establishment at Aldermaston, 50 miles west of London, back to the capital – calling for a ban of nuclear weapons (Figure 5).[37]

In the MRC the drafting of the 1956 report initiated a general discussion of its genetic programme. A Genetics Research Committee was established and the expansion of genetic research became a central

[35] See Tobias C. Carter, "Early days of MRC radiation genetics in retrospect," talk presented at the 25th anniversary of the occupation of the buildings of the Radiobiology Unit at Harwell, 20 March 1979; MRC Library, Harwell. On the test ban debate see Divine, 1978.

[36] See http://bellona.no/en/energy/nuclear/sellafield/wp_5-2001/21871.html, downloaded on 1 March 2005. Surprisingly, Lorna Arnold in her authoritative history of the accident concluded that the health impact was much less serious, perhaps even nil; see Arnold, 1992, esp. pp. 152–153. Just a few years before the accident, the government had celebrated the rise of the new nuclear industry issuing a glossy illustrated brochure. The publication underlined the safety of the Windscale factory design; see Jay, 1954.

[37] On the history of CND see Minnion and Bolsover, 1983; and Hudson, 2005; on the nuclear disarmament movement in international perspective see Wittner, 1997.

concern, with money flowing into a variety of existing and new projects.[38] Among the new initiatives was the institution of a Microbial Genetics Unit under William Hayes at Hammersmith Hospital in London and the creation, at the Western General Hospital in Edinburgh, of a Group for Research on the General Effects of Radiation under Court Brown that later became the MRC Clinical and Population Cytogenetics Group. Around the same time Francis Crick, together with Sydney Brenner who was to join him as collaborator, proposed, and received, MRC support for a research programme in the new field of molecular genetics at the Unit for the Study of Molecular Structure of Biological Systems (soon to be renamed Unit of Molecular Biology) in Cambridge. The project took shape with Brenner's move to Cambridge in 1957.[39]

How novel the molecular approach in genetics was and how little it initially impinged on other genetic approaches can be gleaned from the following: The MRC report of 1956 included a detailed description of the "material basis of heredity", but DNA, even less so the double helix, were not mentioned.[40] The only time "molecules" were mentioned in the text was in the statement that "mutations... are believed to be due sometimes to chance disturbance of the complex molecules which constitute the genes".[41] More explicit reference was made to chromosome breakages and structural rearrangements of chromosomes as an effect of radiation. The MRC report was written to be accessible to politicians and government officials, yet the fact that no effort was made to introduce the new findings on DNA structure indicates that this level of explanation was not (yet) seen as providing a useful handle for assessing radiation damage. The DNA model proposed by Watson and Crick and

[38] The setting up of the Genetics Research Committee that was to advise and assist the MRC in the promotion and development of work in the field of genetic research was decided in 1956, but its actual appointment was postponed to May 1958, when Peter Medawar was able to assume the chairmanship. The creation of the committee had been suggested by the Genetic Panel of the Committee on Hazards to Man of Nuclear and Allied Radiation and hence followed directly from work on the White Paper. The newly created committee consisted of two panels, an experimental genetics panel and a human genetics panel that was mainly concerned with epidemiological research. Both panels met several times until 1960. By 1963 the general feeling was that the MRC was "no longer in any need of being convinced of the importance of genetic research" and the committee was disbanded; see P. Medawar to J. Faulkner (MRC), 21 May 1963, FD1/7844, National Archives. On the new opportunities for genetic research see also Research in genetics, 1957.

[39] Chadarevian, 2002, pp. 190–198.

[40] Medical Research Council, 1956, pp. 24–28.

[41] Ibid., p. 26.

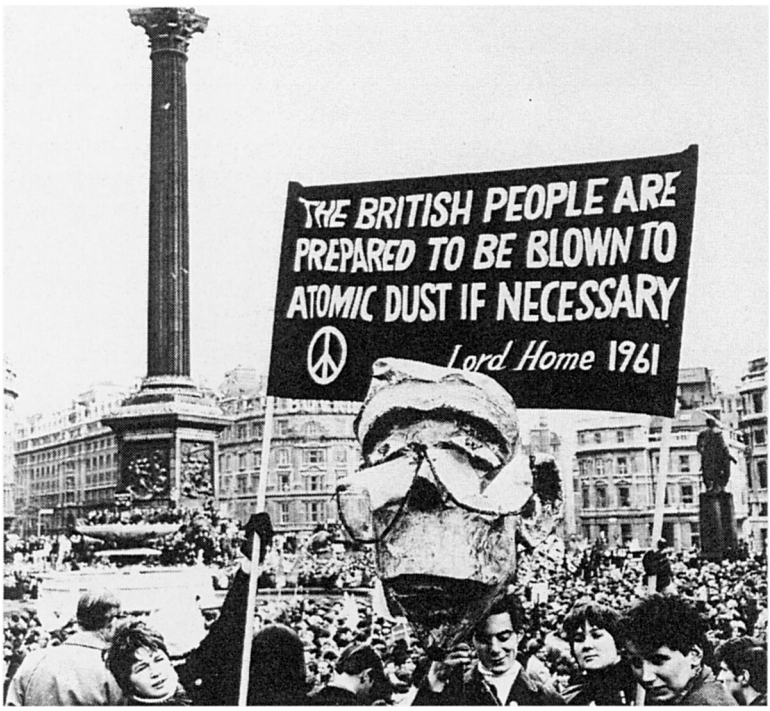

Figure 5. CND Easter March gathering at Trafalgar Square in London. The distinctive logo, created by artist and CND member Gerald Holtom, was first adopted for use at the 1958 march to Aldermaston. It has since served as CND logo as well as to symbolise nuclear disarmament and peace worldwide. Source: CND picture archive. Courtesy of CND.

later research in molecular genetics offered explanations of how mutations could occur, but it did not prevent other approaches to mutation detection to be pursued in parallel.

A follow-up report that the MRC published under the same title in 1960 again did not mention DNA but included an appendix that reported about new findings that established that human cells contained 46 chromosomes instead of 48 as had been believed for many years.[42] The quick consensus that gathered around this finding precipitated a flurry of new work in human cytogenetics in which radiobiologists actively participated. The new chromosome pictures and especially the picture of the human karyotype as standardised in a series of conferences in the early 1960s became an iconic image of genetics at the time.

[42] Medical Research Council, 1960, Appendix C, p. 59. On the history of chromosome counting see Kottler, 1974; and, more recently Martin, 2004.

Only much later was it supplanted by the double helix, but even then did chromosome research, on the morphological as well as on the molecular level, continue.[43] More importantly, viewed from the 1950s, the rise of human chromosome and DNA research must be seen in the context of a growing interest in genetic research, precipitated by pressing concerns about the threat of nuclear radiations.

Raising the Stakes

While the MRC report on the effects of radiation on humans commissioned by government was in preparation, and then again around the Windscale accident, the work of the MRC unit at Harwell featured repeatedly in the media. A full-page article in the *Oxford Mail* assured the public "that every possible effect of nuclear danger to human beings is being investigated".[44] The mice irradiation experiments attracted special attention.

The Genetic Section under Carter used the increased public awareness of the threat of radiation and the policy developments at the MRC to propose an ambitious 10-year programme involving another five-fold expansion of the genetics work at Harwell. The plans had been in the drawer since 1955 but the MRC wanted to postpone the decision on the proposal until after the general revision of its genetic programme undertaken by the Genetics Panel of the committee drafting the White Paper. It now looked favourable at the proposal. In his submission to the MRC Carter proposed to expand the ongoing chronic low-dose gamma irradiation experiments to include not only the irradiation of adult male but also of adult female mice and foetuses.[45] In addition, the group suggested to study mutagenesis in microorganisms and drosophila and to start mice and drosophila population studies. The idea behind the population experiments was to study not just the *incidence* of mutations but also the effect of mutated genes on the phenotype. The effects were thought to depend on the interaction with other genes and

[43] The interplay between the two traditions of genetic research and their link to the radiation concerns of the 1950s will be further explored elsewhere.

[44] Costello, 1955.

[45] The initial restriction to the irradiation of male mice had practical reasons that were linked to the differences in the reproductive physiology of the two sexes. The use of the sperm of irradiated male mice instead of the whole organisms in breeding experiments was economical and speeded up the production of the next generation. The exclusive irradiation of male mice none the less provided only a partial picture of the effects of radiation on the population. Later investigations indicated that the mutation rate in female mice was lower than in their male counterparts.

the environment, including other organisms. These complex interactions could only be studied at the level of populations. As a first approach to the problem Carter proposed to study changes of fitness in irradiated mice and drosophila populations by observing mating behaviour and establishing fertility rates. The experiments were to be performed in specially designed "population cages" in which a system of interconnecting galleries gave the animals the liberty to choose their own mates.[46]

The mice experiments together required an expansion of the population from 1 to 5 million mice (a figure of 10 million also appeared), a total of 68 breeding rooms (up from 13 existing ones) with 200 cages each plus ancillary rooms for cage washing and sterilizing, increased laboratory space and additional staff. Experience suggested that for the specific loci experiments a team of one scientist, one laboratory technician and two animal technicians could deal with the work of five 200-cage mouse breeding rooms. The plans called for eight new such teams. Overall the staff of the Genetic Section was expected to grow from the existing 15 workers to 67.[47] The breeding rooms were to be fitted with fluorescent instead of the usual tungsten lighting; mechanical ventilation, close temperature control and alarm system, standby electrical heating, washing facilities and floor drainage – all of which added greatly to the costs of the planned extension. Cambridge physicist James Chadwick related to a somewhat worried Cockcroft that the only precaution "the great professor Fisher" at Cambridge was taking about his mice for genetic experiments was against cats and that he saw no need for temperature control in the British climate.[48] Carter's firm view was that the cost of the biological experiments, although substantial, was "very low compared with that of research on the physical aspects of ionising radiations" – neutron generators costing a lot more than mouse cages – and that the "great importance to future human generations of adequate radiation genetic research now [underlined in original] justifies a very considerable expenditure".[49] The Genetics Research Committee also highlighted the moral obligation to press ahead with the work because of its important implications for human protection as well as

[46] "Progress report 1954–1957 of the Radiobiological Research Unit," MRC.57/816; MRC Library, Harwell.

[47] T. C. Carter, "Staff and accommodation required for the proposed genetic research programme at Harwell," 6 November 1956, and "Expansion of genetics research in the Radiobiological Research Unit," MRC.56/915; FDI/8706, National Archives.

[48] J. Chadwick to J. Cockcroft, 14 Feb 1958; AB6/658, National Archives.

[49] T. C. Carter to Dr Loutit, 27 January 1955; F. 380, Joseph S. Mitchell Papers, Cambridge University Library.

the UK's international obligations since the plan for the experiments had already been communicated to the United Nations.[50]

Quite independently of these discussions, the Atomic Energy Authority that so far provided accommodation for the unit, but aimed at restricting growth on the Harwell site, was not prepared to pay for the new expansion. There had been strains in the relationship of the two institutions all along. A special point of contention regarded the charges the MRC unit had to pay to the Atomic Energy Authority for the use of the piles and other facilities. The MRC considered at length the pros and cons of remaining on the Harwell site.[51] In the end it was decided that the unit would remain housed on grounds of the Atomic Energy Authority and hence in close proximity of the atomic energy facilities, but in a building funded and administered by the MRC (Figure 6). By that time the Atomic Energy Research Establishment, through its Technical Irradiation Group, had started its own, rapidly expanding programme of biological research, including genetical investigations.[52]

Before the new facilities were inaugurated, Carter had decided to leave the unit and take up a position in the poultry industry. The career change was perhaps less dramatic than one might assume at a first glance and instead highlighted the extent to which the two activities overlapped. Animal breeding and stock maintenance were an integral part of the genetics experiments conducted at Harwell while the poultry industry was increasingly taking on board genetic knowledge.[53] Carter's move may well have been driven by his desire to increase his personal income. However, the persistent difficulties regarding the exchange of data with the colleagues at Oak Ridge and the problems this posed for the continuation of the mice experiments at Harwell may well have provided additional reasons for abandoning the work.

A personal statement drafted by Carter and submitted as confidential document for discussion to the MRC Genetics Research Committee in 1958 revealed the extent to which Anglo-American relations dominated, and threatened to undermine, the mice irradiation experiments at Harwell. In Carter's view the main problem regarded the relative magnitude of the British and American efforts in the field of mouse

[50] Committee on Experimental Genetics, Minutes of the first meeting held on Tuesday, 24th June, 1958, MRC.58/688, CEG/58/6; file FD1/7839, National Archives.

[51] T. C. Carter to J. Cockcroft, 11 February 1958, "Siting–MRC's radiation genetics work"; ABA16/914; also H. Himsworth to J. S. Mitchell, 28 April 1959; FDI 2/293, National Archives.

[52] T. Carter to H. Himsworth, 14 April 1958; FD1/8706, National Archives.

[53] On the increasing role of genetics in poultry production see Boyd, 2001.

radiation genetics. Mouse mutagenesis experiments, and especially the low-dose specific-locus studies, were "brute force experiments", that is their execution depended strictly on the number of available cages. For every British cage there existed 16 American cages. That meant that "if the British start an experiment, and it looks promising, and they disclose the fact to the Americans, it would always be possible for the Americans to start a similar experiment later and yet have it finished first". The document went on to list in detail the many occasions in which cooperation had been hampered and trust had been misused. The reluctance of the American team at Oak Ridge to share data was increasingly interpreted as depending on political reasons and security restrictions rather than on personal erratic behaviour.[54]

With Carter's departure his ambitious project was never realised as such, but the mice irradiation studies at Harwell continued under John Searle's and Mary Lyons' supervision well into the 1990s.[55] The investigations used increasingly sophisticated techniques aimed at establishing the types and amounts of genetic damage that occurred under various irradiation regimes and in relation to various parameters such as sex, age and stages in the cell cycle. The results were incorporated into subsequent international reports on protection issues and eventually found their way into textbook accounts.[56]

In many respects the test ban treaty of 1963 marked the end of the fallout debate but the question of the long-term effects of low-dose radiation persisted. In 1972 reports of both the U.S. National Academy

[54] "Committee on Experimental Genetics, annex 1 to minutes of second meeting held on 21st October, 1958. Personal statement by Dr T. C. Carter on Anglo-American relations over programmes for research in mouse radiation genetics, 1947–1968," MRC.58/978; file FD1/7842, National Archives. Even under the McMohan Act of 1946 that severely restricted technical cooperation in nuclear matters between British and U.S. scientists, allowance was made for the exchange of information on medical and public health matters. The principle was reinforced in the *modus vivendi* agreement of 1948; see Gowing, 1974a, pp. 112, 245–252, 266–272. Yet the results of biological research often impinged on aspects of nuclear politics and for this reason could be retained. For a sobering example of data release restriction in radiobiological research under the AEC see Whittemore, 2001. To my knowledge research under the MRC was never classified.

[55] In the 1980s, Robin Mole, Loutit's successor as director of the MRC Radiobiology Unit who had by then retired, apparently considered once more launching a "mega-mouse project" to settle the threshold question, but nothing came out of it. Oral communication, Harwell, April 2003.

[56] See for instance the widely used textbook on human genetics by Curt Stern that from its first edition in 1949, contained a whole chapter on "The genetic hazards to radiations" that was updated in later editions to incorporate the latest findings; see Stern, 1949; 2nd edition, 1960; 3rd edition, 1973.

Figure 6. New MRC building at Harwell. Source: MRC News, March 1985, no. 26, p. 4. Courtesy of the MRC.

of Science National Research Council's Advisory Committee on the Biological Effects of Ionizing Radiation and the United Nations Scientific Committee on the Effects of Atomic Radiation, the so-called BEIR and UNSCEAR reports, dismissed direct attempts to study low-dose effects. They argued that investigating effects so small and so ambiguous seemed not only difficult but was also unlikely to yield significant health benefits.[57] Yet the issue did not go away. In the late 1970s, with the expansion of atomic energy programmes in various countries, the question of the long-term (somatic and genetic) effects of continuing low-dose radiation from external sources or from radioisotopes accumulated in the body flared up again. While discussions on a "safe threshold" had long given way to the establishment of a "permissible dose", the precise (genetic and somatic) effects of low-level exposure (now defined as 5 rems or less) continued to be debated. The issue remains controversial to the present day, despite the advent of refined molecular technologies to assess mutational changes.[58]

Re-Organisation and Legacies

In 1968 the MRC reviewed its programme in radiation biology that by that time accounted for 6% of its total budget with the Harwell unit

[57] Hacker, 1994, p. 254.

[58] As example see the recent controversy surrounding the publication of a report on the possible cause of childhood leukaemia, commissioned by the former Labour environment minister Michael Meacher. The point of accusation concerns the suppression of data indicating that the increased incidence of leukaemia in children might be due to low-dose radiation from nuclear power plants; see Brown, 2004b.

occupying the biggest chunk of it. The review led to a drastic reduction of the Harwell unit. Only research that, even if fundamental in nature, was directly relevant to protection issues was to remain on the Harwell site. All other research was to be integrated into academic research programmes. At the same time the access of external users to the radiation facilities was to be improved. This last measure reflected the increased demand of atomic energy sources for biological research.

The decision to size down the Harwell unit impacted especially on the cytogenetics group under Charles E. Ford that had entertained close collaborative links with the Genetic Section. A trained botanist, Ford had moved to Harwell in 1949, after a three-year stint at the Department of Atomic Energy at Chalk River, Canada, where he had studied the biological hazards of radiation using as material the roots of the broad bean, *Vicia faba*. Once at Harwell, Ford and his collaborators set out to develop the technologies to study radiation-damaged chromosomes in mammalian cells. The development of new techniques allowed Ford in 1956 to be the first to confirm new data published by Joe-Hin Tjio and Albert Levan in the same year that indicated that the number of human chromosomes was 46 and not 48 as previously reported. The Swedish group had made their observation on cultured cells from human lung tissue. Ford's use of fresh tissue of human testis eliminated any speculation about the general applicability of the new chromosome count. Ford, in collaboration with the physician Paul Polanyi, also published the first papers on chromosome abnormalities in human syndromes, including the Turner and Klinefelter syndromes. These and connected findings represented a crucial step in the introduction of genetic diagnostic techniques into the clinic. Other important studies of the group regarded the observation of radiation induced chromosomal changes in blood and bone marrow cells and of the chromosomes in mouse tumor cells.

Despite the move of this significant group to Oxford, in the following decades the remaining operation at Harwell grew into a key centre of genetics research in the UK. In a further re-organisation of the unit in the mid-1990s, the Radiobiological Research Unit was reconstituted as two new units incorporating the two areas of particular strength: the Radiation and Genome Stability Unit, studying the genetic effects of radiations (now on DNA level), and the Mammalian Genetics Unit which incorporated the UK MRC Mouse Genome Centre, involved in genetic studies of the mouse as well as in administrating the Frozen Mouse Embryo and Sperm Archive. Particular emphasis in that unit lay on mouse models of human genetic diseases. With circa one thousand

different mice mutants (corresponding to 360,000 mouse embryos) in the bank and about 200 different mutants in the animal house, the mutant collection of the Mouse Genome Centre at Harwell ranks as the largest in Europe. The Atomic Energy Research Establishment itself has been decommissioned and the site is now redeveloped into the Harwell International Business Centre.

Researchers in the MRC unit at Harwell started adopting DNA technologies in the 1980s. By that time recombinant DNA technologies offered new tools to assess mutational changes on the molecular level. However, these studies did not completely supersede the work done before the adoption of the new techniques. Rather, the new studies built in several ways on the previous work.

The mutant collection started with the irradiation experiments in the 1950s. It got going more seriously in the 1970s with the introduction of the more powerful mutagenic agent ENU (an urea compound) and, concurrently, the development of novel freezing techniques, which made it possible to maintain mutant strains in the form of frozen embryos. Parallel to the isolation of mutants, extensive functional knowledge of mutations was accumulated over the years. The *Mouse Newsletter*, launched at Harwell in 1947, listed and described mutants and published linkage data. It appeared until a few years ago, when other web-based initiatives building on the completed mouse genome took over its function. The mutant collection and the functional knowledge it embodies, are gaining new importance in the post-genomic era. They are needed for the functional analysis of the sequence information that has been accumulated. The collection is set to grow. Ideally there should be one mutant for every point mutation. The establishment of the mouse as model organism for human diseases also dates back to the radiation experiments of the 1950s.[59] In all these respects current genetic practices build on research traditions, tools and institutions of postwar radiation genetics.

On a more general level, as the history of the "genetics experiment" indicates, genetic research received its political and public prominence in the 1950s due to its close associations with nuclear politics and the concerns it generated. Atomic energy posed new questions and offered new opportunities for genetic research. In many respects the tools and problems of atomic energy set the agenda for genetics after the war. At the same time, investigations on the genetic hazards of radiation defined the risks and fuelled the fears of atomic energy. The research impinged

[59] See Rader, 2004. On the mouse as model organism for human diseases see also Gaudillière, 2003.

directly on aspects of nuclear politics as well as on the public response to it as exemplified by the global fallout debate that led to the atmospheric test ban treaty. The low-dose irradiation experiments of the 1950s did not produce the clear-cut answers researchers and politicians hoped to find, but they laid the ground for an expanding field of research. Together with other investigations, including the studies of the survivors of the atomic attacks on Japan and the chromosome mutation studies of the 1950s, they firmly link the history of genetics to the atomic age.

Acknowledgments

I thank Professor Dudley Goodhead for a first introduction to the history of the MRC Unit at Harwell, Mary Lyons for sharing her memories of the early mouse work in the unit, Peter Glenister for introducing me to the history of the mouse mutant and the frozen embryo and sperm collection, Maureen Bulman at the MRC library at Harwell for her invaluable help in locating relevant material and Adrian Ford, Kevin Glover and Steve Thomas of Imaging Service MRC Harwell for supplying scans. Earlier drafts of the paper were presented at seminars and conferences in London, Vienna, Manchester, Princeton, Harvard and Berlin. I thank the participants and especially John Beatty, David Cantor, Jenny Marie, Hans-Jörg Rheinberger and Alexander von Schwerin as well as Angela Creager and Maria Santesmases for many insightful comments and suggestions. Special thanks to Skuli Sigurdssen for careful reading and many stimulating discussions.

References

Arnold, L. 1992. *Windscale 1957: Anatomy of a Nuclear Accident*. New York and London: St Martin's Press.

Beatty, J. 1991. "Genetics in the Atomic Age: The Atomic Bomb Casualty Commission, 1947–1956." K.B. Benson, J. Maienschein and R. Rainger (eds.), *The Expansion of American Biology*. New Brunswick: Rutgers University Press, pp. 284–324.

—— 1993. "Scientific Collaboration, Internationalism, and Diplomacy: The Case of the Atomic Bomb Casualty Commission." *Journal of the History of Biology* 26: 205–231.

—— 1994. "Opportunities for Genetics in the Atomic Age." Paper presented at the Fourth Mellon Workshop, Institutional and Disciplinary Contexts of the Life Sciences, MIT, Cambridge, Mass., April 1994.

The Biological Effects of Atomic Radiation: A Report to the Public. 1956. Washington, D.C.: National Academy of Sciences–National Research Council.

Boyd, W. 2001. "Science, Technology and American Poultry Production." *Technology and Culture* 42: 631–664.

Brown, P. 2004a. "Fission Vision." *Society Guardian* 2 June, p. 12.

—— 2004b. "Meacher Rails at 'Biased' Cancer Report." *The Guardian* 8 September, p. 11.

Carlson, E.A. 1981. *Genes, Radiation, and Society: The Life and Work of H. J. Muller*. Ithaca, N.Y: Cornell University Press.

Costello, P. 1955. "Harwell Team Investigating Atomic Radiation." *Oxford Mail* 1955, 12 April.

Chadarevian, S.de 2002. *Designs for Life: Molecular Biology After World War II*. Cambridge: Cambridge University Press.

Divine, R.A. 1978. *Blowing on the Wind: The Nuclear Test Ban Debate*. New York: Oxford University Press.

Edgerton, D.E.H. 1992. "Whatever Happened to the British Warfare State? The Ministry of Supply, 1945–1951." H. Mercer, N. Rollings and J.D. Thomlinson (eds.), *Labour Governments and Private Industry. The Experience of 1945–1951*. Edinburgh: Edinburgh University Press, pp. 91–116.

Effect of Radiation on Human Heredity: Report of a Study Group Convened by WHO together with Papers by Various Members of the Group. 1957. Geneva: World Health Organization.

Falconer, D. 1993. "Quantitative Genetics in Edinburgh, 1947–1980." *Genetics* 133: 137–142.

Fowler, J.M. (ed.) 1960. *Survival: A Study of Superbombs, Strontium 90 and Fallout*. London: MacGibbon & Kee.

Gaudillière, J.-P. 2003. "Making Heredity in Mice and Men: The Production and Uses of Animal Models in Postwar Human Genetics." J.-P. Gaudillière and I. Löwy (eds.), *Heredity and Infection: The History of Disease Transmission*. London: Routledge, pp. 181–202.

Genetics Conference. Committee on Atomic Casualties. National Research Council. 1947. "Genetic Effects of the Atomic Bombs in Hiroshima and Nagasaki."*Science*, 10 October: 331–333.

Gowing, M. 1974a. *Independence and Deterrence: Britain and Atomic Energy, 1945–1952: Vol. I: Policy Making*. London: Macmillan.

—— 1974b. *Independence and Deterrence: Britain and Atomic Energy, 1945–1952: Vol. II: Policy Execution*. London: Macmillan.

Hacker, B.C. 1987. *The Dragon's Tail: Radiation Safety in the Manhattan Project, 1942–1946*. Berkeley: University of California Press.

Hacker, B.C. 1994. *Elements of Controversy: The Atomic Energy Commission and Radiation Safety in Nuclear Weapons Testing 1947–1974*. Berkeley: University of California Press.

Hamblin, J.D. 2006. "'A Dispassionate and Objective Effort:' Negotiating the First Study on the Biological Effects of Atomic Radiation." *Journal of the History of Biology*, DOI 10.1007/s10739-005-6531-8.

Hudson, K.J. 2005. *CND—Now More Than Ever: The Story of a Peace Movement*. London: Vision Paperbacks.

Jay, K.E.B. 1954. *Britain's Atomic Factories. The Story of Atomic Energy Production in Britain*. London: Her Majesty's Stationery Office.

Jolly, J.C. 2003. *Thresholds of Uncertainty: Radiation and Responsibility in the Fallout Controversy*. PhD dissertation, Oregon State University.

Kay, L. 2000. *Who Wrote the Book of Life? A History of the Genetic Code*. Stanford: Stanford University Press.

Kevles, D.J. 1995. *In the Name of Eugenics: Genetics and the Uses of Human Heredity*. New York: Harvard University Press.

Kopp, C. 1979. "The Origins of the American Scientific Debate Over Fallout Hazards." *Social Studies of Science* 9: 403–422.

Kottler, M.J. 1974. "From 48 to 46: Cytological Technique, Preconception, and the Counting of Human Chromosomes." *Bulletin of the History of Medicine* 48: 465–502.

Kraft, A. 2006. "Between Medicine and Industry: Medical Physics and the Rise of the Radioisotope 1945–1965." *Contemporary British History* 20: 1–35.

Lindee, S. 1994. *Suffering Made Real: American Science and the Survivors at Hiroshima*. Chicago: Chicago University Press.

Martin, A. 2004. "Counting as an Epistemic Theme in the History of Human Chromosomes." *Social Studies of Science* 34: 923–948.

Medical Research Council 1956. *Hazards to Man of Nuclear and Allied Radiations*. London: Her Majesty's Stationery Office. Cmd 9780.

—— 1960. *The Hazards to Man of Nuclear and Allied Radiations. A Second Report to the Medical Research Council*. London: Her Majesty's Stationery Office.

Minnion, J. and Bolsover, P. (eds.) 1983. *The CND Story: The First 25 Years of CND in the Words of the People Involved*. London: Allison and Busby Limited.

Muller, H.J. 1946. *Nobel Lecture, December 12, 1946*. http://nobelprize.org/medicine/laureates/1946/muller-lecture.html; accessed 7 March 2005.

Neuberger, J. 1998. *Radiation in MRC Supported Research in the 1950s and 1960s*. London: Medical Research Council.

Nuclear and allied radiation (hazards to man): Motion, Parliamentary Debate of 16 July 1956. 1956. In *Parliamentary Debates (Hansard). Fifth Series-Volume 556. House of Commons. Official Report*. London: Her Majesty's Stationery Office, pp. 928–975.

Nuclear explosions (genetic effects), Parliamentary debate of 22 March 1955. 1955. In *Parliamentary Debates (Hansard). Fifth Series-Volume 538. House of Commons. Official Report*. London: Her Majesty's Stationery Office, pp. 1881–1947.

Olby, R. 2003. "Quiet Debut for the Double Helix." *Nature* 421: 401–405.

Paul, D.B. 1987. "'Our Load of Mutations' Revisited." *Journal of the History of Biology* 20: 321–335.

Pirie, A. (ed.) 1958. *Fall Out: Radiation Hazards from Nuclear Explosion: Revised Edition Including a Report on the Windscale Disaster and an Analysis of the United States Congress Report on Radioactive Fall Out and its Effects in Man*. London: MacGibbon & Kee.

Pound, N. 1994. *A Permissible Dose? Ionising Radiation as a Genetic Hazard, Great Britain, 1935–1960*. M.Phil dissertation., Faculty of Modern History: Oxford University.

Rader, K. 2004. *Making Mice: Standardizing Animals for American Biomedical Research, 1900–1955*. Princeton: Princeton University Press.

Rasmussen, N. 1997. "Midcentury Biophysics: Hiroshima and the Origins of Molecular Biology." *History of Science* 35: 244–293.

Research in Genetics. 1957. In *Report of the Medical Research Council for the Year 1955–1956*. London: Her Majesty's Stationery Office, p. 9.

Schwerin, A.V. 2004. *Experimentalisierung des Menschen. Der Genetiker Hans Nachtsheim und die vergleichende Erbpathologie 1920–1945*. Göttingen: Wallstein Verlag.

Stern, C. 1949. *Principles of Human Genetics*. San Francisco.

—— 1960. *Principles of Human Genetics*. San Francisco: W. H. Freeman and Company.
—— 1973. *Principles of Human Genetics*. San Francisco: W. H. Freeman and Company.
Walker, J.S. 2000. *Permissible Dose: A History of Radiation Protection in the Twentieth Century*. Berkeley: University of California Press.
Weart, S. 1988. *Nuclear Fear: A History of Images*. Cambridge, MA: Harvard University Press.
Whittemore, G. 2001. "The Multidimensional Chess of Science and Society: A Postwar Debate Over Plutonium Exposure." G.E. Allen and R.M. Macleod (eds.), *Science, History and Social Activism: A Tribute to Everett Mendelsohn*. London: Kluwer, pp. 277–289.
Wittner, L.S. 1997. *Resisting the Bomb: A History of the World Nuclear Disarmament Movement, 1954–1970*. Stanford, CA: Stanford University Press.